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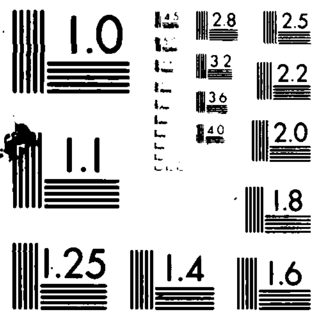

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MANUAL REVERSION FLIGHT CONTROL SYSTEM
FOR A-10 AIRCRAFT:
PILOT PERFORMANCE AND SIMULATOR CUE EFFECTS

By

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March 1982

Final Report

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The A-10 aircraft incorporates an emergency backup control mode, the Manual Reversion Flight Control System (MRFCS). Maintaining effective control in this mode is a demanding pilot task, but it is not practiced in the flying training syllabus. Because current plans call for training this skill using simulation, information was needed on simulator cue requirements. Accordingly, the research objective was to determine the effectiveness of selected simulator visual and force cues used by experienced A-10 pilots to maintain aircraft control and to land when in the MRFCS mode. The study found that (a) a large field of view enhanced the pilot's control of the aircraft, (b) platform motion had no influence upon aircraft control, (c) aircraft control was more difficult in the MRFCS mode than in the simple single engine failure state, (d) point of failure was a significant variable reliably affecting pilot control of the aircraft, and (e) pilot performance improved as a function of practice (trials).

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PREFACE

This research was performed to satisfy requirements of Air Force Human Resources Laboratory Technical Planning Objective 3, the thrust of which is air combat tactics and training. The general objective of this thrust is to identify and demonstrate cost-effective training strategies and training equipment capabilities for use in developing and maintaining the combat effectiveness of Air Force aircrew members. More specifically, the research was part of that conducted under the Air Combat Training Research subthrust, whose goal is to provide a technology base for training high level and quickly perishable skills in simulated combat environments. Work Unit 11231114, A-10 Manual Reversion Flight Control System (MRFCS) Research, addressed a portion of this subthrust, namely, improved mission survival in combat. Mr. James F. Smith was the project scientist, and Dr. Thomas H. Gray was the principal investigator.

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MANUAL REVERSION FLIGHT CONTROL SYSTEM FOR A-10 AIRCRAFT: PILOT PERFORMANCE AND SIMULATOR CUE EFFECTS

I. INTRODUCTION

The definition of simulator cue requirements is a topic of continuing interest to designers of aircrew training devices (ATDs). The lack of a comprehensive data base often requires that a specific study be performed to provide design data for a particular ATD development program. As an example, the present study was conducted to produce information that could be used to develop cue requirements criteria for operational ATD specifications.

Background

The purpose of an ATD is to provide training that transfers positively to the aircraft. Although this training is always intended to be efficient and effective, the ATD may not provide adequate training for some tasks. Normally, this situation is satisfied through instruction and practice in the aircraft, but in the case of training for certain malfunctions and emergency procedures, the risks of training in the actual aircraft are too great (or too costly). In these instances, the only viable training option is some form of simulation.

An excellent illustration of the case in point is found by consideration of the A-10 aircraft and its associated subsystems. The A-10 was specifically designed for the low-level surface attack mission. Because of its potential exposure to damage from ground countermeasures (i.e., antiaircraft artillery and surface-to-air missiles), the A-10 has a manual backup to the "power assisted" primary flight control system. This backup control mode, the Manual Reversion Flight Control System (MRFCS), was designed as an emergency system that would enable the pilot to fly a battle-damaged plane to a safe landing or ejection behind friendly lines.

The inclusion of the MRFCS gives the A-10 an added margin for survival, but aircraft control in the manual flight mode is exceptionally demanding of piloting skills. In fact, as early as 1973, it was reported that there existed an "unacceptable pilot workload for the landing task in the manual reversion mode" (Papa, Douglas, Fortner, & Markwardt, 1973, p. 7). As the flight testing of the A-10 continued, it was found that "the most significant deficiencies noted were unacceptable load factor/pitch attitude excursions encountered during transition from the normal flight control systems to the manual system at high speed. . ." (Papa & Bridges, 1974, p. 6). The final point on A-10 handling qualities is summarized by Unitt, (1976, p. 31), who stated that "pilot initiated transition to manual flight control mode and subsequent flight and landings could be accomplished, but not without an excessive pilot workload."

Because manual aircraft control is so difficult, a critical requirement exists to train A-10 pilots in the management of their aircraft under MRFCS operation. Such training, however, is extremely hazardous and is not currently a part of the initial flight-training program. Explanation of the MRFCS is included in the academic syllabus, but aircraft control in this mode is not practiced in the air until the pilot reaches the operational training unit (and then only to a very limited extent).

Since it was thought too dangerous to instruct MRFCS tasks in the actual aircraft, it seemed logical to transfer this training requirement to an ATD. For this approach to succeed, the simulation must provide the cues required to teach the task. But at the time this study was initiated, a definition of adequate simulator MRFCS cue conditions was not available. Therefore, the soundest method for determining cue requirements to satisfy this unique training objective was deemed to be an empirical test of candidate ATD configurations. The Aeronautical Systems Division (ASD) of the Air Force Systems Command addressed such a request to the Operations Training Division of the Air Force Human Resources Laboratory (AFHRL/OT). Although the primary concern was with the impact of visual (i.e., field of view) and force cueing (i.e., platform motion) variables on pilot performance, the progress and results of training were also of considerable interest.

While research had not been performed on field of view (FOV) and platform motion (PM) simulator cue requirements for A-10 MRFCS applications, some relevant data did exist. For example, a recent review by Martin

(1980) summarized the findings of a number of studies on PM effects in training. In general, for centerline-thrust fighter and trainer-type aircraft, PM was found to have no significant positive impact on training. In one study (Ryan, Scott & Browning, 1978) where PM was found to be beneficial, the effect was limited to performance in the simulator phase of training, and the enhanced performance did not effect transfer to the aircraft. When considering the visual cue component, for the tasks trained in the studies reviewed by Waag, the conclusions seem to follow a general rule: "visual tasks learned in the simulator show positive transfer to the aircraft" (Waag, 1981, p. 17). Because of the role visual factors play in flying tasks, this is not a surprising conclusion. But the effects of FOV (i.e., wide versus narrow angle) on MRFCS-related tasks were unknown. Waag's report indicated that FOV effects might be very modest; consequently, more relevant data were needed.

Objective and Study Rationale

The objective of this research was to determine the effect of selected simulated visual and force cues (specifically variations in FOV and PM) on the ability of combat-ready A-10 pilots to maintain aircraft control and land when in the MRFCS mode. The research emphasized FOV and PM cue requirements for simulated flight in the MRFCS mode; however, further consideration of the issues associated with the MRFCS necessitated an expansion of the number of independent variables to be included in the study. Specifically, three additional areas of interest were identified: (a) the similarity between pilot control performance in the MRFCS and simple single-engine-out flight conditions, (b) the effects of system failure on control performance as a function of occurence when the aircraft is in different flight envelopes, and (c) the ability of pilots to be trained to master the MRFCS.

Fortunately, all of the desired data could be obtained from one economically designed study. This was possible because the flight envelope of the A-10 aircraft when operating in a MRFCS mode is highly restricted. Thus, it followed that the maneuvers, or piloting tasks, which needed to be investigated were limited to basic aircraft control. It was also assumed that the most demanding pilot workloads occur immediately during and after transition from normal control conditions to the MRFCS mode and in landing. Consequently, it was possible to develop a short mission profile that could be flown in 6 to 8 minutes and that would assess pilot performance in these critical periods of flight.

The research needed to be performed as quickly as possible. For this reason, the simulator selected on which to do the work was the Advanced Simulator for Pilot Training (ASPT) available at Williams Air Force Base. Although some engineering effort was required on hardware and software components, ASPT capabilities were successfully expanded to include the MRFCS flight dynamics. Once this was accomplished, the effect of certain simulator cues and aircraft states on experienced pilot performance could be studied in a straightforward manner.

II. METHODS AND PROCEDURES

The primary variables of interest in this study were simulator visual and force cue requirements. Two FOVs and two PM force-cueing methods were employed. The two FOV conditions used were the full ASPT capability (150 degrees by 300 degrees) and a restricted capability simulation consisting of a single window visual system similar to the VITAL III (45 degrees by 35 degrees). The two PM cueing conditions were the total ASPT six-degrees-of-freedom PM system and a zero-degree of platform motion (fixed base) system. Because nearly all current single-seat simulators incorporate g-seat and g-suit capabilities, these force-cueing techniques were present in all ASPT configurations. Thus, the g-seat/g-suit force cueing constituted a fixed condition in the study.

The aircraft control and landing proficiency of combat-ready A-10 pilots were measured under two failure states. The first was a "simple" single-engine failure; the second simulated a true MRFCS mode of flight. Piloting performance was evaluated using a variety of quantitative measures of aircraft flight parameters and system states as dependent variables. The measures were obtained from the ASPT data recording system. All subjects flew the mission profiles under all experimental conditions. The mission profiles were developed by a team of Tactical Air Command pilots and AFHRL/OT instructor pilot personnel. These profiles were tailored to emphasize the unique skill requirements needed to fly the A-10 in the MRFCS mode. Effort was also devoted to testing the objective measures of pilot performances for reliability and validity. The final step involved the use of a test pilot from Edwards AFB to evaluate the MRFCS simulation and to verify that it was representative of the actual aircraft.

Subjects

Twelve TAC pilots from Nellis, Davis-Monthan, and Myrtle Beach AFB were used as subjects. All were qualified as "combat-ready" and had inflight experience with the MRFCS. These pilots had an average of 2,050 total flight hours, of which approximately 1,200 were in fighter-type aircraft. They had an average of 450 hours in the A-10, with a range of 115 to 950 hours.

Apparatus

A detailed description of the basic ASPT system is contained in Cyrus and Fogarty (1978). The A-10 has two hydraulic power systems which are pressurized by two variable delivery, engine-driven pumps. The left hydraulic system is pressurized by the left engine pump, and the right hydraulic system is pressurized by the right engine pump. Pump delivery is a function of engine core revolutions per minute. Loss of one engine results in partial loss of hydraulics. The fully boosted flight control system becomes a manual flight control system when all hydraulic boost is lost.

If the left hydraulic system fails, the following systems are inoperative: flaps, nosewheel steering, normal landing gear operation, normal brakes, and anti-skid. If the right hydraulic system fails, the slats, slipway door, and decelerons are inoperative. In addition, the auxiliary landing gear accumulator and the emergency brake accumulator will not be recharged and the slats will close to a "fail safe" position. Powered control of both elevators, both ailerons, and one rudder is retained after loss of either hydraulic power source.

Six additions to the basic A-10 ASPT configuration were required in order to develop an MRFCS capability:

1. An emergency flight control panel.

2. A stability augmentation panel.

3. A hydraulic control stick simulator.

4. Microcomputers to augment the hydraulic control stick electronics.

5. A software program for the central computer system.

6. An increased iteration rate for the central computer system.

The normal A-10 simulated control system is a fully hydraulically boosted, artificial feel, irreversible control system where the control surface actuators absorb all the aerodynamic force changes. In reverting to a manual, reversible control system, the characteristics of the control system in all three axes change dramatically: consequently, a new math model was needed to simulate pilot control input and control surface response. This math model was developed from wind tunnel and flight test data to faithfully simulate A-10 flight characteristics. These aircraft flight control displacement and pressures were reproduced in the ASPT.

After development and programming, the flight dynamics algorithms were loaded into the updated ASPT computer system which had a 30-hertz computational iteration rate. This speed maintained visual control loading, and flight parameter fidelity. It also permitted the communications with the microprocessor needed to accomplish proper simulations of control loading using the programmable control—loading unit. A digital programming approach allowed the simulation to change from one control-loading program to another almost instantaneously; this was required for the transition from normal flight to manual reversion and then to sustain it.

Simulated Failure States and Aircraft Conditions

With two engines and dual hydraulic systems, the A-10 can suffer a number of failure states. Table 1 shows the engine/flight control conditions which result in normal or failure states. The MRFCS modes are indicated with an asterisk. However, the simulation did not include all these states or the dynamics associated with transition to

these states because the probability of occurrence for some states is low, and the basic questions could be addressed by an investigation of more limited scope.

Table 1. **A-10 Control States**

Hydraulic System Conditions	Engine Conditions[a] Both Engines Operating	Right Engine Fails	Left Engine Fails	Both Engines Fail
Both Hydraulic System Operating	NS	FS-1	FS-2	*FS-3
Right Hydraulic System Fails	FS-4	FS-5	*FS-6	*FS-7
Left Hydraulic System Fails	FS-8	*FS-9	FS-10	*FS-11
Both Hydraulic Systems Fail	*FS-12	*FS-13	*FS-14	*FS-15

[a]NS - Normal State.
FS-Failure State.
*MRFCS Modes.

The actual/MRFCS failure state selected was FS-14. An engineering analysis supported the contention that this failure state was representative of MRFCS flight conditions and also gave realistic tasks for the pilot to perform. At failure onset, the most critical parameters (i.e., aircraft center of gravity and gross weight), as established from engineering data, placed the A-10 in a "sensitive" MRFCS envelope. The single-engine failure state selected was FS-10.

Study Design

In order to produce data representative of real-world operational conditions, it was necessary to plan and conduct a complex multifactor experiment. The experimental design that evolved was a higher-order multivariate repeated measures design. This design was the most economical in terms of resources while still permitting a complete analysis of the effects under investigation. The components of the research design were as follows:

1. Independent Variables. Five different factors were used as independent variables:

a. Field of View. There were two levels of this variable: the ASPT full FOV capability (150 by 300 degrees) and a restricted FOV capability (35 by 45 degrees).

b. Platform Motion. Two levels were studied: the full six-degrees-of-freedom synergistic platform motion system and a stationary platform.

In all simulator configurations, additional force cueing was provided by the existence of g-seat/g-suit simulation. All simulator configurations provided the same aircraft instrument displays and ambient aircraft sounds.

c. Failure States. The two aircraft failure states studied involved failure of the left engine. In one condition, only the left hydraulic system failed; in the second condition, both hydraulic systems failed. The second condition simulates a true MRFCS mode. In both conditions, the failed engine "windmilled."

d. Mission Profiles. In terms of specific piloting tasks, three mission profiles were flown, but all three were variations from a very basic flight pattern. This flight pattern consisted of takeoff, climbing turn, cruise, 3g turn (70-degree bank), descending turn, approach, and straight-in landing. There were three failure points within this profile. The first malfunction could occur during the climbing turn, the second could take place in the 3g turn, and the third could be actuated in the approach (prior to lowering flaps). However, only one failure could occur per trial. The pilot's objective was to regain total aircraft control and safely land as quickly as possible, therefore, this procedure was viewed as producing three separate inflight control tasks that tested pilot performance. Because of

its obvious criticality, the landing portion of the flight profile was isolated as an additional task and separately analyzed. Figure 1 shows the complete flight profile.

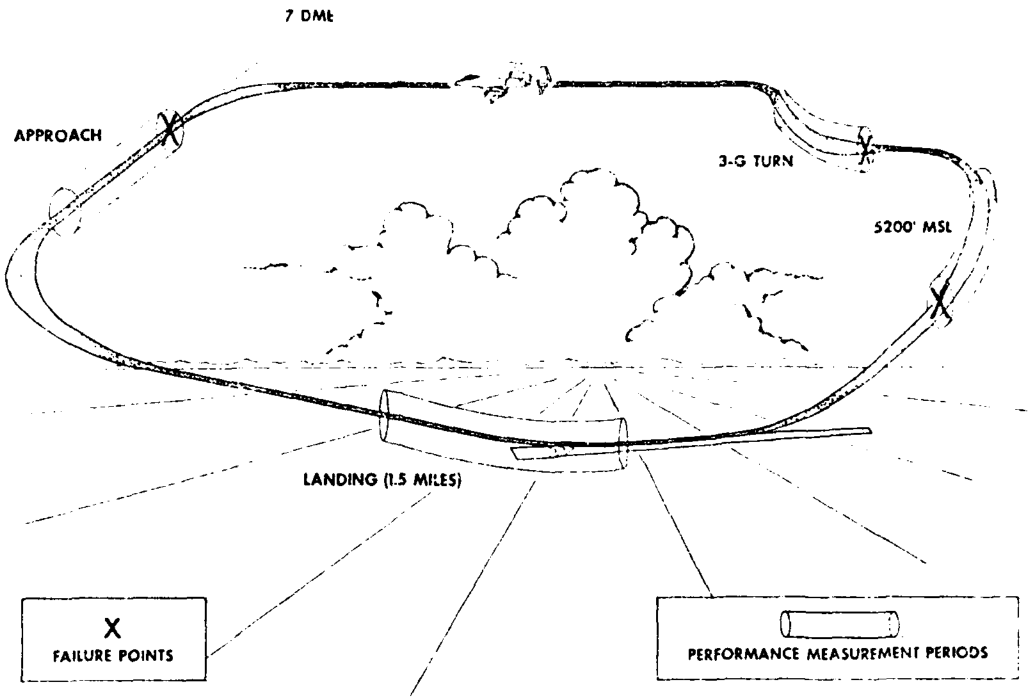

Figure 1. **MRFCS mission profile.**

e. Repetitions. This variable is a measure of practice effects, or learning. Since the landing portion of the mission profile was viewed as a separate task, this could be analyzed by considering each subject to have flown three trials under identical simulator configurations and failure states. Three repetitions are, of course, a minimal number of trials necessary to establish a learning curve, but the design permitted the acquisition of these training data, and they provided a valuable addition to the research.

2. Dependent Variables. The study used two types of dependent variables. The first type was comprised of objective measures of aircraft flight parameters and system state values. The aircraft flight parameters used were bank angle, roll rate, pitch angle, pitch rate, vertical velocity, airspeed, angle of attack, runway centerline deviation, distance from runway threshold, and altitude. The system state values were related to the amount of stress placed on the aircraft. The variables measured were positive and negative g-loading and force on wheels.

Of these 12 quantitative measures, 9 were used to measure the pilot's control of the aircraft as a function of the inflight point of failure. Ten were used to measure pilot control in the landing portion of the flight profile. These dependent variables were unweighted for both the inflight and landing tasks. Table 2 lists these variables, shows what measurement set they were used, and gives their ASPT physical definition.

Table 2. **Listing, Utilization and Definition of Quantitative Variables**

Variable Label	Utilization	Definition
Roll Rate	Inflight, Landing	Radians/second about aircraft (AC) X-axis
Pitch	Inflight, Landing	± degrees from horizontal flight
Pitch Rate	Inflight, Landing	Radians/second about AC X-axis
Vertical Velocity	Inflight, Landing	Feet/second change in altitude
Airspeed	Inflight, Landing	Knots indicated airspeed
Normal Force	Landing	Pressure in pounds on wheels
Angle of Attack	Inflight, Landing	Angle in degrees between AC wing chord and AC velocity vector
Centerline Deviation	Landing	Deviation in feet from runway centerline
Distance Down Runway	Landing	Distance in feet from end of runway marker
Altitude	Inflight	Altitude in feet above ground level
g Load	Inflight	± g-loading on AC
Bank Angle	Inflight, Landing	± degrees about AC X-axis

For inflight control tasks, these measures were sampled at a rate of 30 times per second, and a root mean square (RMS) value was computed. The RMS was selected as the most appropriate statistic because it easily accommodates positive and negative values and is sensitive to (and reflective of) extreme deviations from the central tendency in a distribution of numbers. The same was true for the landing portion of the mission with the exception of force on wheels and distance down runway. These variables were measured by capturing total values.

A final bit of objective data collected during the study dealt with simulator "crashes." The crashes were instances when a total loss of aircraft control occurred while the pilot was transitioning to or landing under the MRFCS mode of flight.

In addition to the objective measures just discussed, subjective measures, based on questionnaire data, were also obtained. At the conclusion of the experimental trials, the subjects were administered a set of forms on which they evaluated the importance and adequacy of the visual and force cues used in the simulation.

Study Procedures

Initially, the subjects were briefed as to the objectives and conduct of the study, a short simulator "safety" course was given, and cockpit strap-in procedures were demonstrated. Each subject then received a training session in ASPT prior to participation in the actual study. This training consisted of two flights (essentially expanded traffic patterns as can be seen from Figure 1) which familiarized the pilot with ASPT characteristics and the mission profile to be flown (see Appendix C). The ASPT was in a normal A-10 configuration. In the study proper, each subject "flew" three missions under four simulator configurations and two failure states. Consequently, there was a total of 24 trials for each subject. The order of presentation of these trials was randomized (to avoid systematic learning or practice effects) and administered over a 2-day period (12 trials per day in blocks of 6). At the conclusion of the experimentation, each subject completed the questionnaires and was debriefed.

Data Analysis

For the objective measures of aircraft control, the statistical model used was a five-factor multivariate analysis of variance with repeated measures on subjects. This 2x2x2x3x12 design was convenient for analyzing both the "inflight" and "landing" data. The same design was used to analyze each dependent variable by means of a univariate analysis of variance, thus producing 9 additional analyses for the inflight data and 10 for the landing data.

The actual data computations were done on the UNIVAC 1108 at the Air Force Human Resources Laboratory. The program used was a modification of the BMDX69 program, which performs a multivariate analysis of variance or covariance for any hierarchical design with equal cell sizes. This included nested, partially nested and crossed, and fully crossed designs. The program also performed univariate tests for each dependent variable. The "crash" data were not statistically analyzed and are reported only in tabular form. The questionnaire data were analyzed by using median rating values to estimate central tendencies and then applying chi-square techniques. The level of significance for all statistical tests was set at the 95 percent level of confidence ($p < .05$).

III. RESULTS

The analyses of the quantitative data collected during the simulated flights are discussed in the first three parts of this section. The first part deals with the inflight failure point data, the second with the landing data, and the third with the "crash" data. The fourth part of this section is concerned with the summary and analysis of the questionnaire data.

As described in the previous section, a repeated measures design was used to analyze the inflight and landing data. For the inflight analysis, the components in the design were: 2 FOVs x 2 PM Conditions x 2 Failure States x 3 Failure Points x 12 pilots. The design components for the landing analysis were 2 FOVs x 2 PM Conditions x 2 Failure States x 3 Trials x 12 pilots. The two sets of data were subjected to both multivariate and univariate analyses of variance.

Analysis of the Inflight Tasks Data

Engine failures were initiated at three points in the flight profile: in the climbing turn, in the 3g turn, and in the approach. Nine dependent variables were used to assess pilot performance on these inflight tasks. Table 3 is an abbreviated listing of the results of the multivariate analysis.

Table 3 shows that there were significant main effects for the FOV, the Failure State, the Failure Point (Tasks), and Subjects. Because individual differences were not of interest in the study, no subject effects or subject-related interactions are discussed. The PM main effect was not significant. There were significant interactions between FOV and Failure Point, Failure State and Subjects, and Failure Point and Subjects. From the multivariate analysis, it may be concluded that in the simulator (a) the full FOV enhances performance, (b) the MRFCS failure state results in poorer performance, (c) maintaining aircraft control in the 3-G turn is more difficult than in the climbing turn or the approach, and (d) the restricted FOV is particularly damaging to pilot performance when the failure occurs in the 3g turn.

The main effect means for each dependent variable used in the analysis of the inflight data are listed in Appendix A. To determine how each dependent variable was affected by the experimental conditions, nine univariate analyses of variance were performed. The design was the same 2x2x2x3x12 paradigm used in the multivariate analysis. In condensed format, the significant sources of variance and their associated probability levels are given in Table 4.

Table 3 Listing of Results of Multivariate Analysis of Variance for Inflight Tasks

Source of Variation	Probability
FOV	.01*
PM	.61
Failure State	.00*
Failure Point (Task)	.00*
Subjects	.00*
FOV X PM	.76
FOV X Failure State	.10
PM X Failure State	.32
FOV X Failure Point	.01*
PM X Failure Point	.09
Failure State X Failure Point	.59
FOV X Subjects	.21
PM X Subjects	.19
Failure State X Subjects	.01*
Failure Point X Subjects	.00*
FOV X PM X Failure State	.50
FOV X PM X Failure Point	.92
FOV X Failure State X Failure Point	.98
PM X Failure State X Failure Point	.65
FOV X PM X Subjects	.82
FOV X Failure State X Subjects	.64
PM X Failure State X Subjects	.90
FOV X Failure Point X Subjects	.75
PM X Failure Point X Subjects	.06
Failure State X Failure Point X Subjects	.73
FOV X PM X Failure State X Failure Point	.79
FOV X PM X Failure State X Subjects	.87
FOV X PM X Failure Point X Subjects	.97
FOV X Failure State X Failure Point X Subjects	.44
PM X Failure State X Failure Point X Subjects	.80

*Statistically significant at required level of confidence ($p < .05$)

Table 4. **Statistically Significant Components From the Univariate Analyses of Variance for Inflight Scores**

Variable	Significant Source of Variance	Probability
Roll Rate	FOV	.01
	Failure Point	.01
	FOV X Failure Point	.05
Pitch	FOV	.025
	Failure State	.01
	Failure Point	.01
	FOV X PM	.025
Pitch Rate	Failure State	.01
	Failure Point	.01
Vertical Velocity	FOV	.025
	Failure State	.01
	Failure Point	.01
Airspeed	Failure State	.01
	Failure Point	.01
Angle of Attack	FOV	.05
	Failure State	.01
	Failure Point	.00
Altitude	PM	.025
	Failure Point	.01
g-Load	FOV	.01
	Failure State	.01
	Failure Point	.01
Bank Angle	FOV	.01
	Failure State	.05
	Failure Point	.01
	FOV X Failure State	.01
	FOV X Failure Point	.01

From the univariate analyses summarized in Table 4 the following conclusions are warranted:

1. For the Roll Rate, the full FOV facilitates pilot control. Control is most difficult when failure occurs in the 3g turn. The FOV X Failure Point interaction shows that the large FOV is particularly beneficial for maintaining control during failures in 3g turns (most difficult) and the approach (medium difficult).

2. For Pitch, the full FOV and simple failure condition allows better control. Control is most difficult when failure occurs in the 3g turn. The FOV X PM interaction indicates that the presence of PM degrades performance with a restricted FOV but improves it with a full FOV.

3. For Pitch Rate, the main effects of Failure State and Failure Point are the same as those found for Pitch.

4. For Vertical Velocity, the main effects are the same as those found for Pitch.

5. For Airspeed, the main effects are the same as those found for Pitch Rate.

6. For Angle of Attack, the main effects are the same as those found for Pitch and Vertical Velocity.

7. For Altitude, the no PM condition produced better pilot control. The significance of this variable at Failure Point is a necessary experimental artifact produced by the flight profiles flown (i.e., failures were programmed to occur at different altitudes).

8. For g-Load, the main effects are the same as those found for Pitch, Vertical Velocity, and Angle of Attack.

9. For Bank Angle, the main effects are the same as those found for Pitch, Vertical Velocity, Angle of Attack, and g-Load. The FOV X Failure State interaction indicated that the restricted FOV is tremendously disruptive of bank control in the true MRFCS failure. The FOV X Failure Point interaction shows that the full FOV is highly beneficial to control of bank for a MRFCS failure in the approach: but control of bank is so poor when there is either a single engine or MRFCS failure in a 3g turn that variations in FOV had no effect.

Analysis of the Landing Task Data

Each subject performed three landings under identical simulator and Failure State configurations. Ten dependent variables were used to assess pilot performance in the landing task. Table 5 is an abbreviated listing of the results of the multivariate analysis and shows that there were significant main effects for (a) FOV, (b) Failure State, (c) Trials (number of times that the landing was repeated), and, (d) Subjects. The PM main effect was not significant. The only significant interaction was between Failure State and Subjects. From the multivariate analysis of the landing data it may be concluded that (a) the full FOV enhances landing performance, (b) landing in the MRFCS mode is more difficult, and (c) practice improves the pilot's skill in landing. The main effect means for each dependent variable used in the analysis of the landing data are listed in Appendix B.

Table 5. **Listing of Results of Multivariate Analysis of Variance for the Landing Task**

Source of Variation	Probability
FOV	.00*
PM	.59
Failure State	.00*
Trials	.04*
Subjects	.00*
FOV X PM	.85
FOV X Failure State	.19
PM X Failure State	.74
FOV X Trials	.43
PM X Trials	.66
Failure State X Trials	.77
FOV X Subjects	.19
PM X Subjects	1.00
Failure State X Subjects	.05*
Trials X Subjects	.12
FOV X PM X Failure State	.62
FOV X PM X Trials	.84
FOV X Failure State X Trials	.64
PM X Failure State X Trials	.81
FOV X PM X Subjects	.67
FOV X Failure State X Subjects	.27
PM X Failure State X Subjects	.43
FOV X Trials X Subjects	.72
PM X Trials X Subjects	.68
Failure State X Trials X Subjects	.18
FOV X PM X Failure State X Trials	.66
FOV X PM X Failure State X Subjects	.95
FOV X PM X Subjects	.96
FOV X Failure State X Trials X Subjects	.65
PM X Failure State X Trials X Subjects	.93

* Statistically significant at the required level of confidence ($p < .05$).

Ten univariate analyses of variance, one for each dependent variable, were performed. The design was the same 2x2x2x3x12 paradigm used in the multivariate analysis. As in the inflight analyses, only the significantly different sources of variation are shown in Table 6. From the *univariate analyses*, the following conclusions are warranted:

Table 6. **Statistically Significant Components from the Univariate Analysis of Variance for Landing Scores**

Variable	Significant Source of Variance	Probability
Roll Rate	FOV	.01
	Failure State	.025
	Trials	.01
	FOV X Trials	.05
Pitch	FOV X PM X Trials	.05
Pitch Rate	FOV	.05
	Failure State	.01
	Trials	.01
Vertical Velocity	FOV	.05
	Failure State	.025
	Trials	.01
	FOV X Trials	.05
Air Speed	Trials	.025
Normal Force	None	-
Angle of Attack	FOV X PM X Trials	.01
Centerline Deviation	None	-
Distance Threshold	None	-
Bank Angle	FOV	.01
	Failure State	.01

1. For the Roll Rate, the full FOV and the simple failure facilitate pilot control. Landing skill improves as a function of practice. The FOV X Trials interaction shows that the rate of control improvement was greater with a large FOV.

2. The higher order interaction for Pitch indicates that, in conjunction with the large FOV, PM has a beneficial effect on performance, except for the second trial in the small FOV condition.

3. For Pitch Rate, the main effects are the same as those found for Roll Rate.

4. For Vertical Velocity the main effects are the same as those found for Roll Rate and Pitch Rate. The FOV X Trials interaction is interpreted as for Roll Rate, above.

5. For Airspeed, the data show that it decreased as a function of increasing practice.

6. The Normal Force on wheels dependent variable did not show any significant differences.

7. When Angle of Attack is considered, one higher-order interaction is significant. The FOV X PM X Trials interaction indicates that, although the combination of a large FOV and PM generates a condition that favors superior control; under these conditions, repeated practice did not improve the pilot's ability.

8. The Centerline Deviation dependent variable did not show any significant differences.

9. The Distance Threshold dependent variable did not show any significant differences.

10. For Bank Angle, the main effects for FOV and Failure State are the same as those found for Roll Rate, Pitch Rate, and Vertical Velocity.

Crash Data

The crash data also provide evidence of control mode differences and pilot learning, but since a "crash" is an all-or-none occurrence, these effects must be viewed in an absolute and discrete sense. Table 7 presents the mean number of crashes per pilot at various stages of practice. The data in this table illustrate the difficulty of flight control in the MRFCS mode. The effects of practice are also well portrayed. The last entry in Table 7 points up a lesson learned in the study. A pilot, no matter how skilled or confident, should never "sideslip" an A-10 in the MRFCS mode to make a landing.

Table 7. **Mean Crashes Observed for Subjects**

Performance Period	Crashes per Pilot in Simple Failure Mode	Crashes per Pilot in MRFCS Mode
1. First Session (Trials 1-6)	.00	.83
2. Second Session (Trials 7-12)	.00	.33
3. Third Session (Trials 13-18)	.00	.00
4. Fourth Session (Trials 19-24)	.00	.08

Analysis of the Questionnaire Data

The purpose of the questionnaires (see Appendix D) was to provide information that would supplement the data recorded during the actual simulator flights. The nature of such information is highly subjective, but it was believed that, by providing a forum where the pilots could express opinions about, and ratings of, the ASPT MRFCS simulation, other dimensions of measurement could be added to the research. The content of the questionnaires may be subdivided into open-ended queries and rating scales. The open-ended questions were quite general and dealt with simulation "realism" and task difficulty. The rating scales were used to obtain data on simulator handling qualities and the training value of MRFCS practice in the four simulator configurations studied. It was possible to perform simple statistical analyses of these data.

Simulator Handling Qualities: The handling qualities of the simulator were evaluated for both normal and MRFCS flight conditions. These evaluations were performed by the pilots using a five-point rating scale in which a 1 was "too sensitive", a 3 was "like aircraft", and a 5 was "too heavy." In summarizing the results, the median value of these ratings (rounded to the nearest .5) was chosen as the statistic most descriptive of the central tendency shown in the data.

Table 8 gives median ratings of the A-10 ASPT simulation in normal flight conditions. With the exception of being rated as slightly heavy in pitch for the takeoff and climbing turn, it can be seen that the simulation was perceived by the pilots as acceptably realistic.

Table 8. **Median Ratings of ASPT Simulation in Normal Flight**

	Aircraft Axis		
Maneuver	Pitch	Roll	Yaw
Takeoff and Climbing Turn	3.5	3.0	3.0
3g Turn	3.0	3.0	3.0
Landing	3.0	3.0	3.0

The information in Table 9 parallels that in Table 8, but the ratings in Table 9 are assessments of the A-10 simulation in the MRFCS mode. The median ratings assigned by the pilots indicate that the control feel of the MRFCS simulation was also acceptable.

Table 9. **Median Ratings of ASPT Simulation in MRFCS Mode**

Maneuver	Aircraft Axis: Pitch	Roll	Yaw
Takeoff and Climbing Turn	3.0	3.0	3.0
3g Turn	3.0	3.0	3.0
Landing	3.0	3.0	3.0

As the final part of the first questionnaire, the pilots were asked to rate their ability to maintain desired control of pitch, roll, and yaw coordinates while in the MRFCS flight mode. The rating scale used ran from 1 (very well) to 5 (very poorly). A listing of the results (rounded as before) is presented in Table 10. These data show that on the average the pilots felt they were able to maintain reasonable control of these aircraft flight parameters during the execution of the three maneuvers.

Table 10. **Median Ratings of Simulator Control Ability in MRFCS Mode**

Maneuver	Ability to Maintain: Pitch Angle	Roll Rate	Yaw Stability
Climbing Turn	2.5	2.5	3.0
3g Turn	3.0	2.5	3.0
Landing	3.0	3.5	3.5

Training Value of Simulator Configurations

There were four ASPT configurations: full FOV and PM, full FOV and no PM, limited FOV and PM, and limited FOV and no PM. Using a five-point scale (1 equals poor; 5 equals excellent), the pilots rated the value of these four configurations for training the three inflight tasks. The results of this evaluation (rounded to the nearest .5) are shown in Table 11. As the table shows, the ASPT in the full FOV, PM condition was rated as a very good medium for training the selected tasks. The full FOV, no PM configuration gave fair training, but the remaining two conditions were rated as rather "poor."

Table 11. **Median Ratings of Training Value of ASPT Configuration**

ASPT Configuration	Maneuver: Climbing Turn	3g Turn	Approach
Full FOV; PM	4.0	4.0	4.5
Full FOV; No PM	3.5	3.0	3.5
Limited FOV; PM	2.0	1.5	2.0
Limited FOV; No PM	2.0	1.5	2.0

Chi-square analysis isolated the critical simulator configuration component. Table 12 reproduces the actual ratings observed. (Ratings were collapsed into three categories to avoid small expected cell frequencies.) When the chi-square statistical analysis was run on the data in the table the product was a value of 87.63. With six degrees of freedom, a value of 12.60 is significant at the 95 percent level of confidence. Thus it could be concluded that there was a reliable difference in rated training value as a function of ASPT configurations. To determine whether this difference was the result of visual or motion cueing conditions, two additional analyses were required.

Table 12. **ASPT Configuration Training Value Ratings**

ASPT Configuration	Observed Number and Categories of Ratings Category 1 and 2	Category 3	Category 4 and 5
Full FOV, PM	3	12	21
Full FOV, No PM	1	20	15
Limited FOV, PM	27	8	1
Limited FOV, No PM	29	6	1

To investigate visual cue effects, Table 13 recombines the data from Table 12 while equalizing motion cues. From the analysis of the data in Table 13, a chi-square value of 83.52 was obtained. With two degrees of freedom, the critical value at the 95 percent level of confidence equals 6.0. Obviously, the full FOV was rated as yielding significantly better training than did the limited FOV.

Table 13. **ASPT Visual Configurations Training Value Ratings**

ASPT Configuration	Number and Categories of Ratings Category 1 and 2	Category 3	Category 4 and 5
Full FOV	4	32	36
Limited FOV	56	14	2

The data in Table 12 were also used to determine if platform motion was viewed as improving training. In this case, the FOV conditions were equalized. Table 14 presents the data used for this analysis. The chi-square analysis produced a value of 1.72 which, with two degrees of freedom, was not significant at the required level of confidence. Thus the presence or absence of platform motion did not affect the rating of training value.

Table 14. **ASPT Motion Configurations Training Value Ratings**

ASPT Configuration	Number and Categories of Ratings Category 1 and 2	Category 3	Category 4 and 5
PM	30	20	22
No PM	30	26	16

Open-ended Questions: The questionnaire contained three open-ended items. To quote every comment in its entirety would be much too repetitious, so only the essence of these statements is reported.

Item One. *How realistic do you feel the simulation of manual reversion was in this study?* The main themes of the pilots' responses to this question were as follows: "very realistic" . . . "ASPT outstanding" . . . "pretty good, controls not stiff enough" . . . "motion and full FOV gave valuable training" . . . "think it was good" . . . "very good with full FOV and motion" . . .

Item Two. *List any difficulty you encountered in flying under the various simulation modes. Be as specific as possible.* The principal items mentioned were as follows: "small FOV" . . . "stopping aircraft on runway with no brakes" . . . "brakes squirrelly" . . . "poor ground handling characteristics" . . . "motion had no effect" . . . "small FOV meant instrument flight" . . . "motion did not appear to enhance or degrade" . . . "did not notice motion difference" . . .

Item Three. *General Comments.* The following were the major points given in answer to this item: "single engine MRFCS would be rare, but two engine training would be good" . . . "full FOV gives realistic training, small FOV is an impossible task" . . . "motion unnecessary" . . . "simulator convinced me that aircraft can be flown in MRFCS" . . . "big improvement in my performance after three hours of training" . . . "overall, it was a good learning experience" . . .

IV. DISCUSSION

The primary objective of this study was to provide information on the effects of certain flight simulator cue conditions and simulated aircraft states on pilot performance. However, it became apparent that, in addition, information concerning the effects of practice on the acquisition of a skill "untrained" in the aircraft was of at least equal importance. In fact, this second aspect of the study may have the greatest significance in the long run.

The findings of this study have expanded the human factors data base on cue requirements for aircraft simulation. But a lengthy discourse on the importance of FOV and the impotence of PM (for simulator training for an essentially centerline-thrust aircraft) would add little to the existing literature. Flying, as normally performed in an aircraft, is visually oriented for both contact and "instrument" flight conditions. In the contact realm, the question of "How much visual simulation is enough?" can be definitively answered only through costly and painful iterations. However, it is generally accepted that the general principle "more, with greater realism" is usually better. At the same time, it must be remembered that in this study the smaller FOV was judged to have some positive training value. Practice under this condition did improve performance. The small FOV did make the task more difficult but there is little doubt that control of the simulated aircraft in the MRFCS mode can be learned (albeit with great difficulty) with a small FOV.

The fact that PM cueing did not significantly influence pilot performance in the simulator is not surprising. As noted earlier, PM does not seem to play an important role in the simulation of centerline-thrust jet aircraft. The present study provides further confirmation of these previous findings.

If the improvement in pilot skill occurring as a function of performing tasks in the ASPT transfers to the A-10 (as it should), the study may be interpreted as a successful example of a simulator training application. Obviously, if the pilot's capability to perform MRFCS and single-engine-related flight control tasks had not improved, serious doubts would have been cast on the validity of the research.

The distinctive feature of this study is that the task performed in the simulator is one that will probably never be realistically trained or practiced in the aircraft. Although an A-10 pilot might briefly "switch on" the MRFCS while in straight-and-level flight (when at safe altitude in some advanced phase of training), this is not representative of the real world of MRFCS employment and may be of dubious training value. Although many emergency pilot actions are trained in devices other than the aircraft itself, in the majority of cases this training deals only with procedures and not with the development of motor skill sequences. Thus, for the A-10 pilot, it appears likely that his proficiency in the MRFCS mode will be developed and tested in the simulator. Under these circumstances, the simulator is both training device and criterion vehicle. It is this facet of the study that, in large measure, may make it a benchmark for future work.

V. CONCLUSIONS

Because the data analyses produced such clear-cut results unconfounded by complex interactions, drawing conclusions from the study is a simple process. When reduced to its basics, the research may be viewed as investigating simulator configurations, piloting tasks, and practice effects. The findings related to each of these three areas may be succinctly summarized.

1. For simulator configurations and the A-10 failure states, it was found that

a. The large FOV consistently provided an environment in which the pilot's control of the simulated aircraft was significantly superior to control under small FOV conditions.

b. With g-seat and g-suit force cueing present, the addition of the six degrees of freedom PM system did not improve the pilot's control of the aircraft.

2. For piloting tasks, the study produced two very logical results:

a. After an engine failure, maintaining control in the MRFCS mode is more difficult than in a non-MRFCS mode.

b. After an engine failure, maintaining control while in a 3g turn is a harder task than when the failure occurs in a climbing turn or in a normal approach.

3. The data from landings practiced under the same failure state and simulator configurations show that A-10 pilots can be trained to maintain adequate control and land in MRFCS flight modes as well as in simple single-engine-failure flight modes.

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APPENDIX A: INFLIGHT MAIN EFFECT MEANS

Table A-1. **RMS Means for Full and Restricted FOV (Inflight)**

Variable	Restricted FOV	Full FOV
Roll Rate	.13695	.11202
Pitch	8.69007	7.88251
Pitch Rate	.06879	.05331
Vertical Velocity	8.20441	7.15246
Airspeed	182.27250	184.46107
Angle of Attack	9.11427	8.11340
Altitude	2941.60779	2894.54068
G-Load	1.19778	1.16384
Bank Angle	22.97178	19.23351

Table A-2. **RMS Means for PM and No PM (Inflight)**

Variable	Platform Motion	No Motion
Roll Rate	.12218	.12680
Pitch	8.33181	8.24077
Pitch Rate	.06444	.05766
Vertical Velocity	7.57597	7.78090
Airspeed	183.29812	183.43545
Angle of Attack	8.64597	8.58170
Altitude	2956.12384	2880.02466
G-Load	1.17131	1.19032
Bank Angle	20.80275	21.40254

Table A-3. **RMS Means for Single Engine and MRFCS Failures (Inflight)**

Variable	Single Engine Failure	MRFCS Failure
Roll Rate	.11792	.13105
Pitch	7.22590	9.34668
Pitch Rate	.02117	.08093
Vertical Velocity	5.36136	9.99451
Airspeed	187.69297	179.04160
Angle of Attack	7.80535	9.42232
Altitude	2880.16199	2955.98657
G-Load	1.15292	1.20870
Bank Angle	19.97979	22.22550

Table A-4. **RMS Means for Failure Points (Inflight)**

Variable	Climbing Turn	3g Turn	Approach
Roll Rate	.09200	.17885	.10261
Pitch	9.83462	7.56069	7.46356
Pitch Rate	.03554	.09967	.04794
Vertical Velocity	6.81709	9.52848	6.68973
Airspeed	187.41512	194.92847	167.75686
Angle of Attack	6.81427	9.39695	9.63029
Altitude	2984.44128	3607.75797	2162.02460
G-Load	1.03105	1.44681	1.06457
Bank Angle	18.22932	30.70109	14.37754

APPENDIX B: LANDING MAIN EFFECT MEANS

Table B-1. **RMS Means for Full and Restricted FOV (Landings)**

Variable	Full FOV	Restricted FOV
Roll Rate	.04354	.05904
Pitch	5.49833	5.61618
Pitch Rate	.01885	.02009
Vertical Velocity	2.53890	2.82079
Airspeed	144.92545	146.16489
Normal Force	17513.95508	17281.28979
Angle of Attack	7.46288	7.54555
Centerline Deviation	287.73039	721.18256
Distance Threshold	5122.11676	5578.89551
Bank Angle	3.45431	4.60661

Table B-2. **RMS Means for PM and No PM (Landings)**

Variable	Platform Motion	No Motion
Roll Rate	.05106	.05152
Pitch	5.44809	5.66642
Pitch Rate	.01943	.01950
Vertical Velocity	2.65348	2.70620
Airspeed	145.57050	145.51964
Norm Force	17365.61304	17429.63208
Angle of Attack	7.43701	7.57142
Centerline Deviation	464.94418	543.96867
Distance Threshold	5338.82129	5362.19104
Bank Angle	3.82878	4.23213

Table B-3. **RMS Means for Single Engine and MRFCS Failures (Landings)**

Variable	Single Engine Failure	MRFCS Failure
Roll Rate	.05615	.04643
Pitch	5.58407	5.53045
Pitch Rate	.01607	.02287
Vertical Velocity	2.40139	2.95829
Airspeed	145.48868	145.60166
Norm Force	17522.24878	17272.99585
Angle of Attack	7.53821	7.47022
Centerline Deviation	368.64095	640.27181
Distance Threshold	5307.64095	5393.04944
Bank Angle	3.61328	4.44764

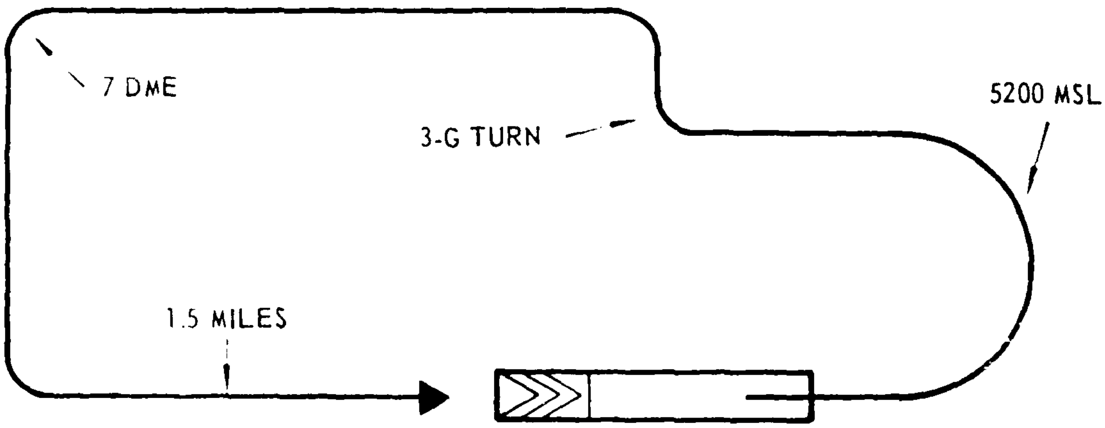
Table B-4. **RMS Means for Trials (Landings)**

Variable	Trial 1	Trial 2	Trial 3
Roll Rate	.05929	.05014	.04444
Pitch	5.65119	5.51109	5.50949
Pitch Rate	.02140	.01920	.01780
Vertical Velocity	2.97416	2.73151	2.33385
Airspeed	148.40395	145.30156	142.93008
Norm Force	16312.91028	17673.36523	18206.59985
Angle of Attack	7.44819	7.54457	7.51989
Centerline Deviation	776.93591	384.87199	351.5616
Distance Threshold	5745.01978	5180.94061	5125.56042
Bank Angle	4.6835	4.03257	3.3753

THE SCENARIO IS AS FOLLOWS:

1. TAKEOFF.
2. CLIMBING LEFT TURN TO HEADING OF 300°
   A. MAINTAIN 200 KNOTS AIRSPEED IN CLIMB.
   B. LEVEL-OFF AT 6000 MSL.
3. PERFORM 3-G, 90° RIGHT TURN: GREATER THAN 60° BANK.
4. LEFT TURN TO HEADING OF 300°
5. LEFT TURN TO FINAL AT 7 DME.
6. MAKE LANDING APPROACH AT MINIMUM OF 150 KNOTS AIRSPEED.
7. LAND.

SCHEMATIC



PRIOR TO EACH TRIAL:

1. SPEED BRAKE CLOSED.
2. FLAPS SET AT 7°
3. GEAR HANDLE DOWN.
4. AUX GEAR EXTENSION HANDLE FULL IN.
5. EMERGENCY BRAKE HANDLE IN.
6. MRFCS SWITCH NORMAL.
7. SET HSI COURSE SELECTOR TO 125.
8. SPEED BRAKE EMERGENCY RETRACT SWITCH IN AFT POSITION.
9. FLAP EMERGENCY RETRACT SWITCH IN AFT POSITION.
10. ALL SAS SWITCHES ON.

APPENDIX D: QUESTIONNAIRES A AND B

MRFCS Study Questionnaire A

Name ______________________________ Rank ______________

ID Number ______________________________ Organization ______________

Administration: 1 2

Previous Flying Experience (as pilot, private and military)

Aircraft Type	Number of Hours
______	______
______	______
______	______
______	______
______	______
______	______

1. A-10 ASPT simulation in normal flight conditions:
Rate simulator control feel for:

	Too Sensitive		Like Aircraft		Too Heavy
a. Takeoff - Turning Climb					
Pitch	1	2	3	4	5
Roll	1	2	3	4	5
Yaw	1	2	3	4	5
b. 3g Turn					
Pitch	1	2	3	4	5
Roll	1	2	3	4	5
Yaw	1	2	3	4	5
c. Landing					
Pitch	1	2	3	4	5
Roll	1	2	3	4	5
Yaw	1	2	3	4	5

2. *A-10 ASPT simulation is MRFCS flight conditions.*
Rate simulator control feel for:

	Too Sensitive		Like Aircraft		Too Heavy
a. Takeoff - Turning Climb					
Pitch	1	2	3	4	5
Roll	1	2	3	4	5
Yaw	1	2	3	4	5
b. 3g Turn					
Pitch	1	2	3	4	5
Roll	1	2	3	4	5
Yaw	1	2	3	4	5
c. Landing					
Pitch	1	2	3	4	5
Roll	1	2	3	4	5
Yaw	1	2	3	4	5

3. In manual reversion, how well were you able to maintain your desired pitch angle during each of the following:

	Very Well		Acceptable		Very Poorly
Climbing Turn	1	2	3	4	5
3g Turn	1	2	3	4	5
Landing	1	2	3	4	5

4. In manual reversion, how well were you able to maintain your desired roll rate during each of the following tasks?

	Very Well		Acceptable		Very Poorly
Climbing Turn	1	2	3	4	5
3g Turn	1	2	3	4	5
Landing	1	2	3	4	5

5. In manual reversion, how well you were able to maintain your stability in yaw during each of the following tasks:

	Very Well		Acceptable		Very Poorly
Climbing Turn	1	2	3	4	5
3g Turn	1	2	3	4	5
Landing	1	2	3	4	5

MRFCS Study Questionnaire B

Name ______________________________ Organization ______________

1. How realistic do you feel the simulation of manual reversion was in this study?

2. Using the attached sheet, circle the number that best rates the training value for each of the modes of simulation flown.

3. List any difficulty you encountered in flying under the various simulation modes. Be as specific as possible.

4. General comments.

5. Have you experienced manual reversion in an aircraft?

	Climbing Turn					3g Turn					Approach				
	P		A		E	P		A		E	P		A		E
Full FOV Motion	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Full FOV No Motion	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Limited FOV Motion	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Limited FOV No Motion	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5

<u>Note</u>
P - Poor
A - Acceptable
E - Excellent

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